Parametrization and resolution issues raised by tropical variability on diurnal to intraseasonal timescales

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1. Introduction

This paper will use two persistent systematic errors in current atmospheric climate models as the basis for presenting ideas on how information from observations of tropical variability can be used to suggest new approaches to improving model simulations in the tropics. The two errors in question are the dry bias over the Maritime Continent and the inability to simulate the Madden Julian Oscillation. The ideas being presented in this paper derive from a synthesis of the results from a variety of research projects being carried out within the CGAM Tropical Group (http://ugamp.nerc.ac.uk/cgam-trop/trophome.html) and which are described in more detail in the referenced papers.

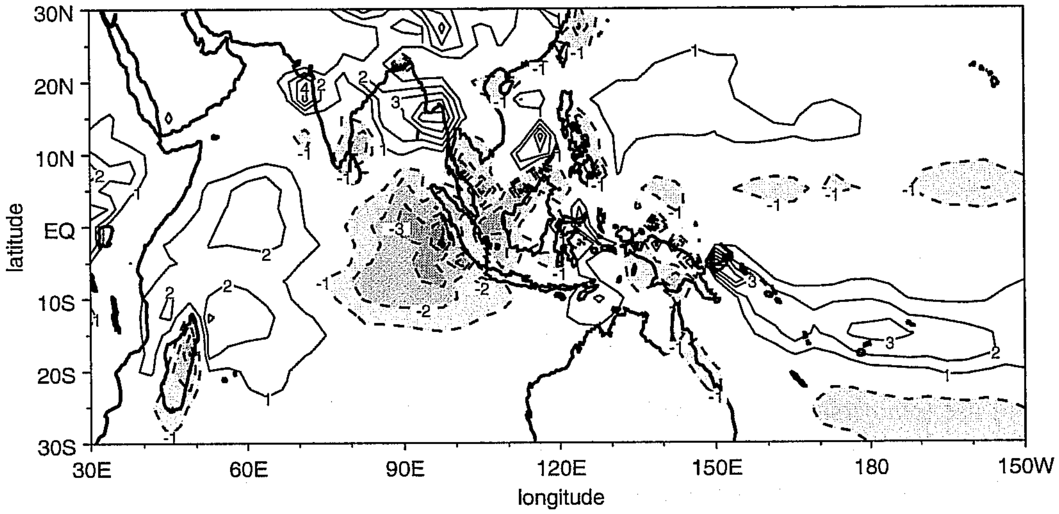
The main tools used in these projects are the Met Office Unified Model (UM) and a variety of global observational datasets. Version HadAM3 of the UM (see Pope et al. 1999) is used for the various modeling experiments. Precipitation data from the CPC Merged Analysis of Precipitation (CMAP; Xie and Arkin 1996) and ECMWF Reanalyses (ERA-15) are used to evaluate the model performance. A new multi-year global dataset of window (11μm) brightness temperature from multiple satellites has been developed by the European Union Cloud Archive User Service (CLAUS) project. The utility of such data for investigating the space-time variability of tropical convection has been demonstrated by, for example, Salby et al. (1991). In our case, the availability of 3-hourly data has enabled the construction of a climatology of the diurnal cycle in convection, cloudiness and surface temperature for all regions of the tropics (Yang and Slingo 2001). This has proved critical for identifying potential processes in the tropics that are not well represented in climate models.

2. The maritime continent and its role in the global circulation

The Maritime Continent, with its complex system of islands and shallow seas, presents a major challenge to models, which tend to systematically underestimate the precipitation in this region (Figure 1 (a); Neale and Slingo 2002). Neale and Slingo (2002) argued the deficient rainfall over the Maritime Continent could be a driver for other systematic errors, such as the excess precipitation over the western Indian Ocean. To demonstrate the sensitivity of global systematic model errors to the heating in this region, Neale and Slingo (2002) performed two experiments, one with the existing distribution of islands and a second where the island grid-points are replaced by sea grid-points with SST interpolated from existing adjacent grid-point values. Both experiments were run for 17 years using observed SSTs for 1979-95, as in the second phase of the Atmospheric Model Intercomparison Project (AMIP II).

In the absence of the Maritime Continent islands, the local precipitation increases, reducing the existing dry bias and bringing the model closer to observations (Figure 1 (b)). In response to this improved heating distribution, precipitation decreases over the West Indian Ocean and SPCZ regions, reducing the systematic wet bias in these regions. This supports the hypothesis that tropical systematic errors are often related through vertical (Walker) circulations.

(a) Annual mean systematic error



(b) Precipitation change

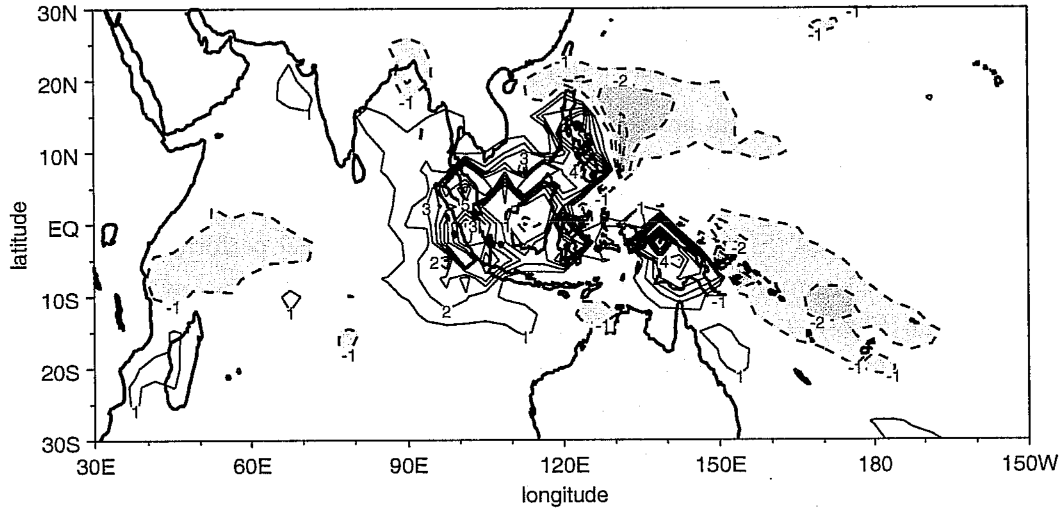


Figure 1: (a) Annual mean systematic error in precipitation (mm/day) from HadAM3 based on 17-year (1979-95) integration with observed SSTs. (b) Change in annual mean precipitation from an integration of HadAM3 in which the islands of the Maritime Continent have been replaced with ocean grid points. From Neale and Slingo (2002).

The extra-tropical response to changes in the tropical heat source is also well demonstrated by these experiments. The enhanced heating and hence divergent outflow over the Maritime Continent generates Rossby waves which have a significant impact on northern hemisphere winter surface temperatures across much of North America and the North East Eurasian region (Figure 2). These changes in mid-latitude circulation and surface temperature are such as to substantially reduce model systematic error in these regions. These results reinforce the critical role played by the Maritime Continent in the global circulation, and emphasize the importance of considering the global context of model systematic error in which biases in the tropics may be a key factor.

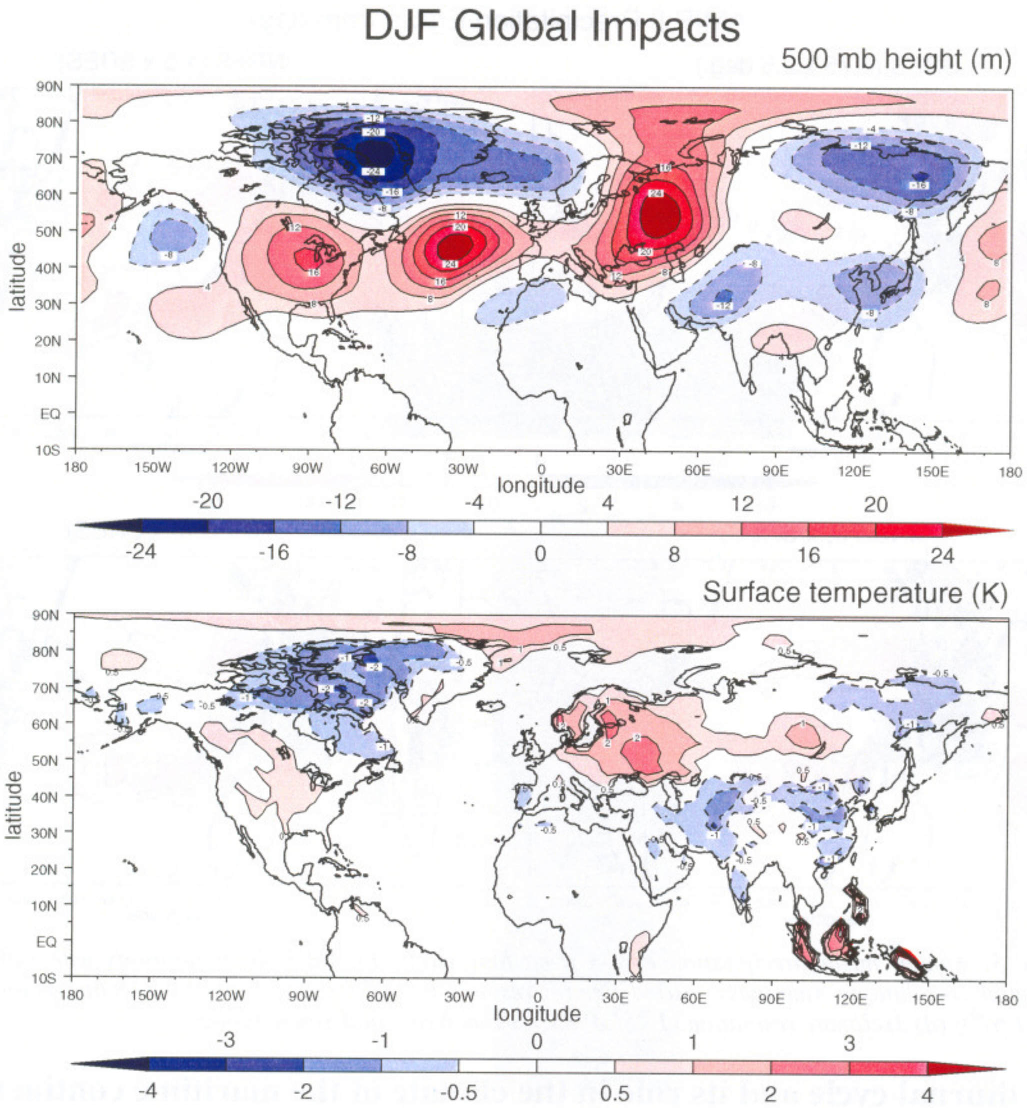


Figure 2: Seasonal mean differences averaged for 1979-95 between the sensitivity AMIP II experiment with the maritime continent land grid-points removed and the control AMIP II experiment; (a) DJF northern hemisphere 500-hPa geopotential height (m), and (b) DJF northern hemisphere surface air temperature (K). From Neale and Slingo (2002).

It could be argued that this system of islands is poorly resolved at the coarse climate resolution of the model, but Neale and Slingo (2002) further showed that even with a three-fold increase in horizontal resolution there is no improvement in the dry bias of the model; if anything it seems to get slightly worse (Figure 3). Additionally, the anomalously wet regions in the SPCZ and north and west of the Philippines are worse in the experiments with the highest resolution. The results in Figure 3 demonstrate very clearly the persistence of model errors and reinforce the notion that increasing resolution is not a panacea for model error, with the suggestion that deficiencies in the representation of the physical system are primarily responsible.

The results summarized above clearly show that the Maritime Continent heat source is a key component of the global climate, and that improvements in its simulation may have significant impacts on remote systematic errors. The fact that many models show similar problems over the Maritime Continent suggests that they all lack some key ingredient. Neale and Slingo (2002) hypothesized that the diurnal cycle over the islands and the complex circulation patterns generated by land-sea contrasts may be crucial for the energy and hydrological cycles of the Maritime Continent. This hypothesis was based on new results pertaining to the diurnal cycle, which are described in the following section.

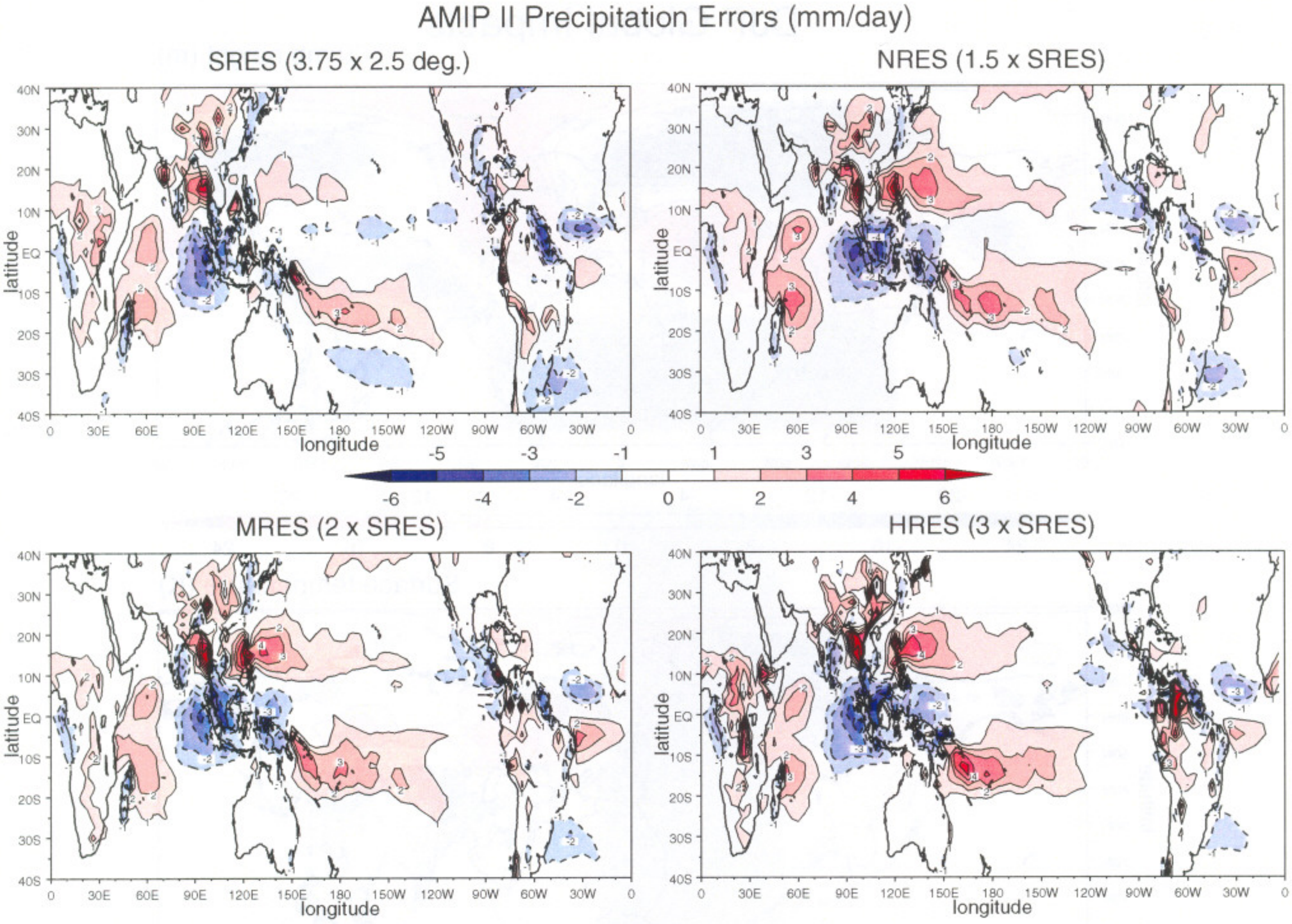


Figure 3: Annual mean precipitation errors from four HadAM3 AMIP II integrations with different horizontal resolutions (mm/day); (a) Climate resolution ($3.75^{0}x2.5^{0}$); (b) 1.5xclimate resolution ($2.5^{0}x1.67^{0}$); (d) 3xclimate resolution ($1.25^{0}x0.83^{0}$). From Neale and Slingo (2002).

3. The diurnal cycle and its role in the climate of the maritime continent

As noted earlier, the CLAUS dataset provided the basis for a detailed study of the diurnal cycle across the global tropics. The diurnal cycle dominates the sub-seasonal variability over tropical and subtropical continents and systematically modifies the precipitation over the tropical oceans (see Yang and Slingo (2001) and references therein). In common with previous observational studies, the CLAUS climatology of the diurnal cycle has shown that oceanic deep convection tends to reach its maximum in the early morning. Continental convection generally peaks in the evening, although there are interesting regional variations, indicative of the effects of complex land-sea and mountain-valley breezes, as well as the life cycle of mesoscale convective systems.

A striking result from this analysis of the diurnal cycle of brightness temperature and estimated precipitation[1] in the CLAUS dataset has been the extent to which the strong diurnal signal over land is spread out over the adjacent oceans (Figure 4). These coherent signals can be seen for several hundred kilometres and in some instances, such as over the Bay of Bengal, can lead to substantial diurnal variations in convection and precipitation. Looking in detail at specific regions, Figure 5 shows the phase of the diurnal harmonic, expressed as the local time of maximum brightness temperature (i.e. minimum convection). In Figure 5(a), lines of constant phase spread out south eastwards across the Bay of Bengal, starting from the north east coast of India. The inferred propagation speed is between 15 and 20ms^{-1}, in line with those of coherent

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[1] Estimated precipitation is calculated using the threshold technique for estimating tropical deep convective precipitation, developed by Hendon and Woodberry (1993), which relates cold cloud brightness temperature to an equivalent precipitation rate. See Yang and Slingo (2001) for more details.

disturbances, which were observed propagating rapidly southwards over the Bay of Bengal during the recent Joint Air-Sea Monsoon Interaction Experiment (JASMINE; Webster et al. 2002). These propagating disturbances generate significant diurnal variations in precipitation over the Bay of Bengal, suggesting that these waves have a fairly deep structure. In fact, the inferred propagation speed is consistent with that expected for a diurnally generated gravity wave whose equivalent depth is 40 metres and whose spatial scale is wavenumber 20.

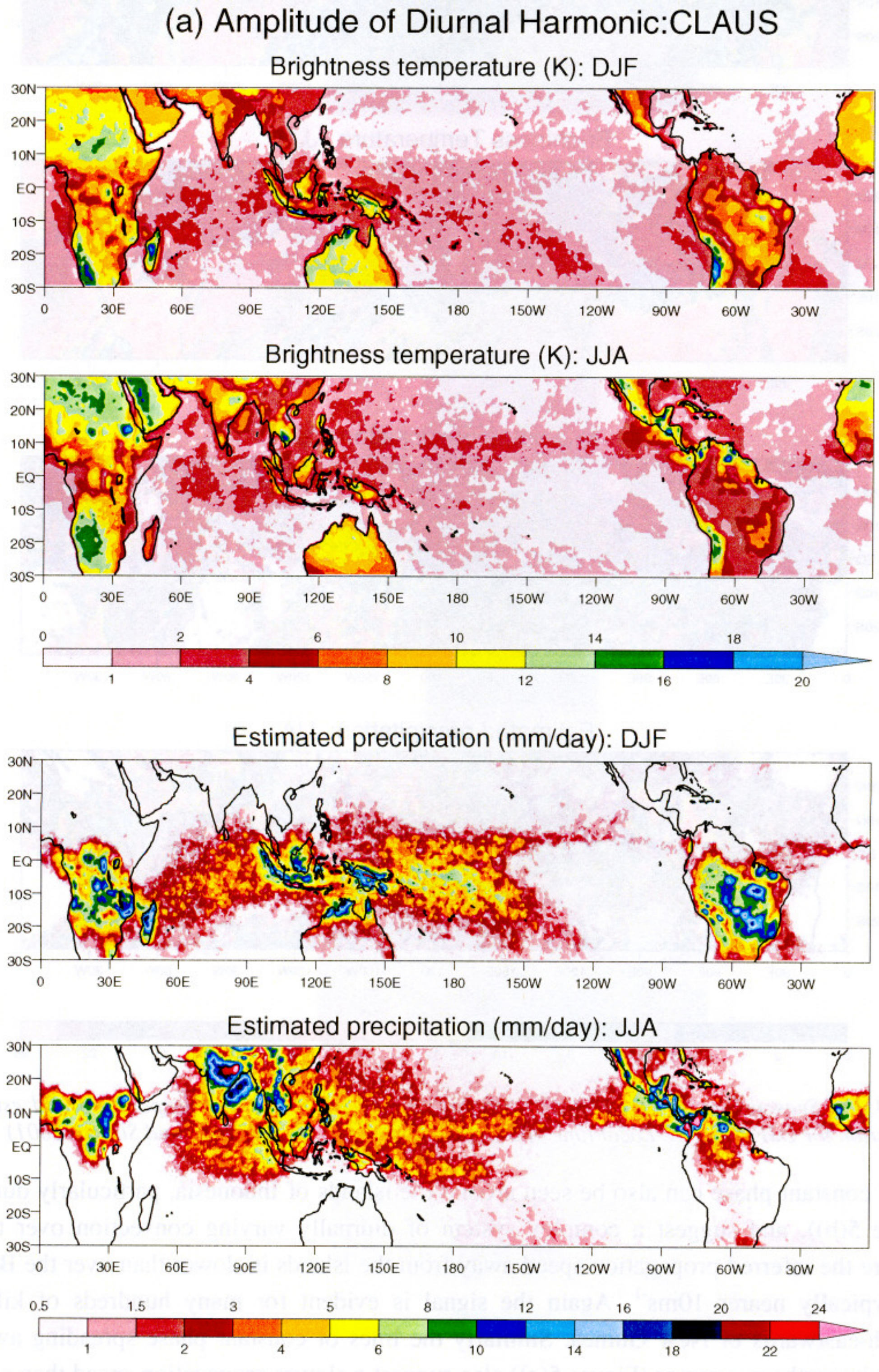


Figure 4: (a) Seasonal mean amplitude of the diurnal harmonic in brightness temperature (K) and estimated precipitation (mm/day) for DJF and JJA.

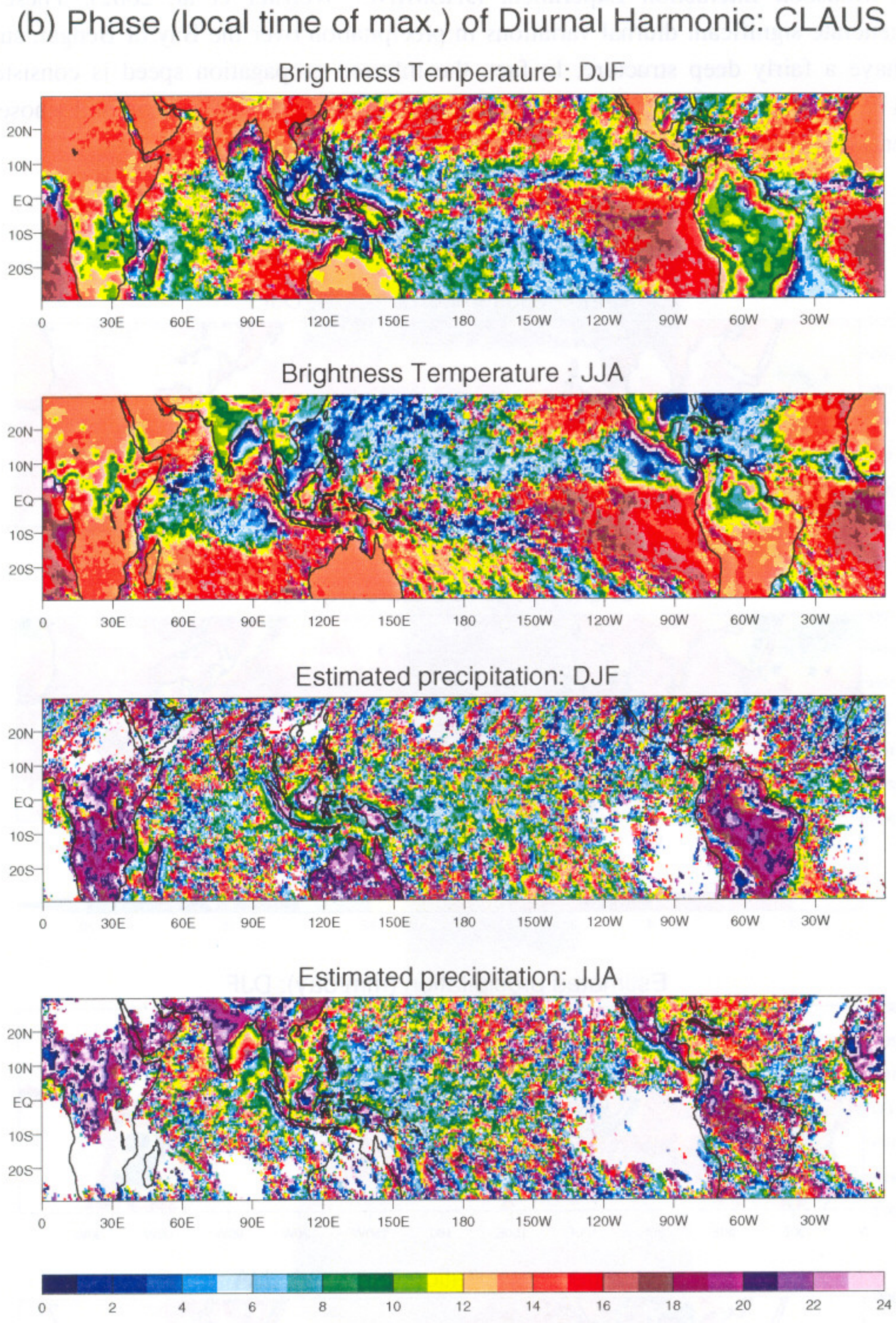


Figure 4. (b) Seasonal mean phase of the diurnal harmonic of brightness temperature and estimated precipitation for DJF and JJA. Local time of the maximum is given. From Yang and Slingo (2001)

These lines of constant phase can also be seen around the islands of Indonesia, particularly during northern winter (Figure 5(b)), and suggest a complex system of diurnally varying convection over the Maritime Continent. Here the inferred propagation speed away from the islands is slower than over the Bay of Bengal case, being typically nearer 10ms^{-1}. Again the signal is evident for many hundreds of kilometres, for example, north-eastwards of New Guinea. Similarly the lines of constant phase spreading away from the Mexican coast in northern summer (Figure 5(c)) also suggest a slower propagation speed than seen in Figure 5(a) for the Bay of Bengal. If the signal is associated with a gravity wave, then the slower speed is probably indicative of a shallower wave, more typical of a sea/land breeze effect.

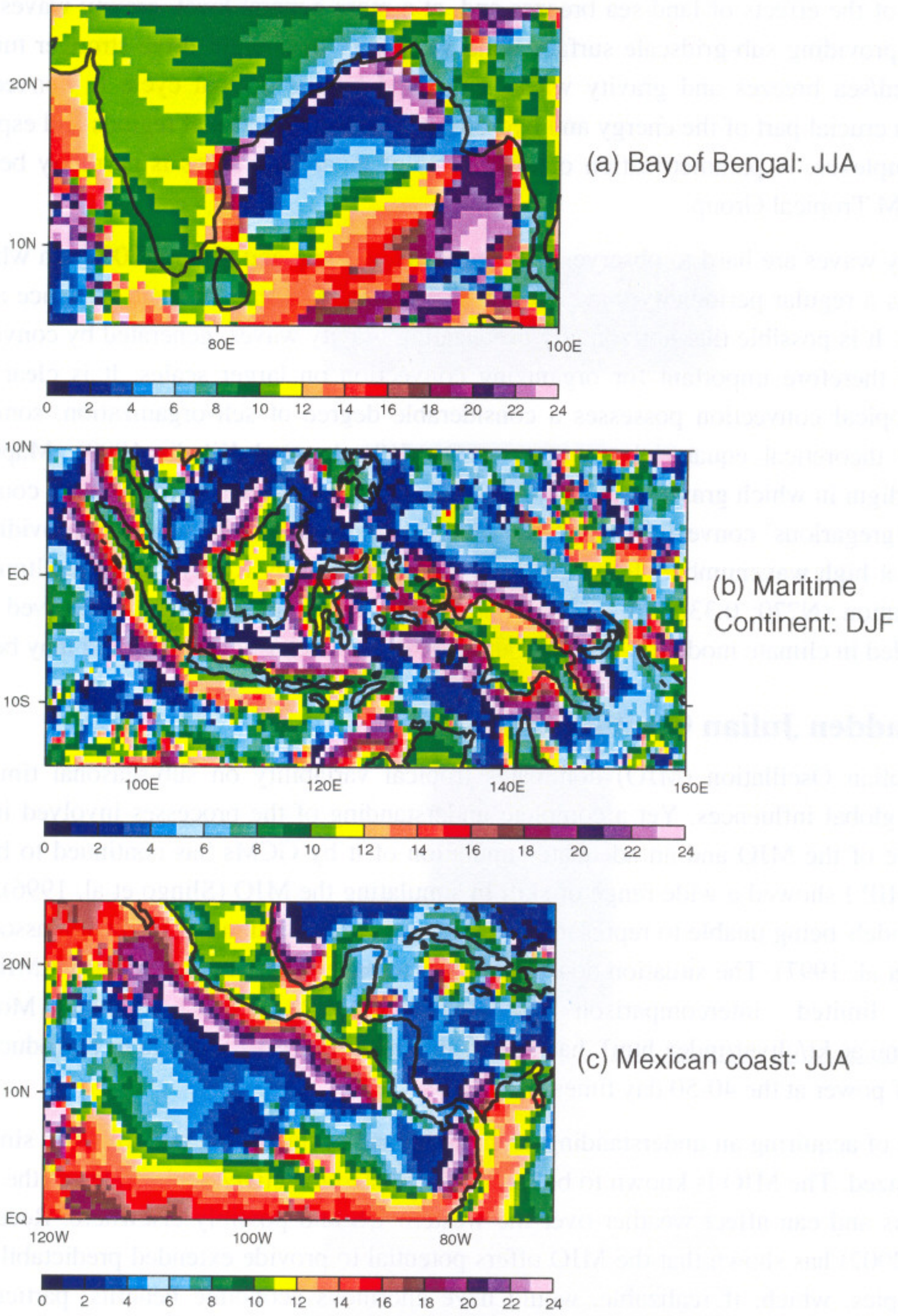


Figure 5: Phase of the diurnal harmonic of brightness temperature over (a) Bay of Bengal in JJA, (b) Maritime Continent in DJF, and (c) Mexican coast in JJA. Phase is given in terms of the local time of the maximum. From Yang and Slingo (2001)

Over the complex system of islands which make up the Maritime Continent, these coherent signals in the diurnal cycle provide compelling evidence of important land-sea breeze and gravity wave effects, which may play a crucial role in the heat and moisture budget of this key region for the tropical and global circulation (see discussion in Section 2). The presence of these signals has been confirmed recently in an analysis of TOGA-COARE data by Liberti et al. (2001) who showed that the signal of the diurnal cycle over New Guinea could be detected in the wind and cloud fields up to 600km from the coast. Again, the average speed of propagation of the features was around 15ms^{-1} in agreement with the results of Yang and Slingo (2001).

The results of the studies by Neale and Slingo (2002) and Yang and Slingo (2001) point to the need for a parametrization of the effects of land-sea breezes and, at a more general level, gravity waves for triggering convection and providing sub-gridscale surface wind variability that might drive stronger turbulent fluxes. Specifically, land/sea breezes and gravity waves generated by the diurnal cycle in convection over the islands may be a crucial part of the energy and hydrological budgets of coastal regions and especially around large island complexes. A parametrization of the effects of land/sea breezes is currently being developed within the CGAM Tropical Group.

Normally gravity waves are hard to observe, but the results of Yang and Slingo (2001), in which the source of the waves has a regular periodicity, have provided important evidence of their existence and interaction with convection. It is possible that horizontally propagating gravity waves, generated by convection, may be widespread and therefore important for organizing convection on larger scales. It is clear from satellite imagery that tropical convection possesses a considerable degree of self-organization, some of which is associated with theoretical equatorial wave structures (Wheeler and Kiladis 1999). Mapes (1993) has provided a paradigm in which gravity waves or buoyancy bores, generated by convection, could give rise to, as he called it, 'gregarious' convection. The potential importance of gravity waves in providing the upscale energy transfer at high wavenumbers has recently been pointed out by Koshyk and Hamilton (2001), based on a high resolution (N270; $0.33^0 \times 0.4^0$) GCM simulation. How the effects of unresolved gravity waves should be included in climate models is unclear, but the use of a stochastic forcing field may be appropriate.

4. The Madden Julian Oscillation

The Madden Julian Oscillation (MJO) dominates tropical variability on sub-seasonal timescales and is known to have global influences. Yet a complete understanding of the processes involved in the initiation and maintenance of the MJO and an adequate simulation of it by GCMs has continued to be elusive. The results from AMIP I showed a wide range of skill in simulating the MJO (Slingo et al. 1996), with even the most skillful models being unable to represent the large-scale organization of convection associated with the MJO (Sperber et al. 1997). The situation does not appear to have improved much since AMIP I. The results of a more limited intercomparison by the CLIVAR Asian/Australian Monsoon Panel (http://climate.snu.ac.kr/clivar/index.htm), has shown that models are still unable to reproduce the observed concentration of power at the 40-50 day timescale.

The importance of acquiring an understanding of the MJO and of improving our ability to simulate it cannot be over-emphasized. The MJO is known to be intimately related to active/break cycles of the Australian and Asian Monsoons and can affect weather over the western US and possibly elsewhere. Recent research by Waliser et al. (2002) has shown that the MJO offers potential to provide extended predictability up to 15-20 days in the tropics, which, if realizable, would have enormous economic benefits, particularly for crop management and health. For the coupled ocean-atmosphere system, associated westerly wind events generate ocean Kelvin waves, which may significantly modify the evolution and amplitude of El Nino, as was the case in 1997 (e.g. McPhaden et al. 1999). Because of the influence of the MJO on equatorial ocean dynamics, the large interannual variability in the activity of the MJO has implications for the predictability of the coupled ocean-atmosphere system (Slingo et al. 1999).

Recent research has pointed to possible avenues that might lead to improvements in the simulation of the MJO. Firstly, Inness et al. (2001) have shown that the simulation of the MJO is significantly improved in an atmospheric version of the UM when the vertical resolution is increased. Secondly, there is good evidence that the MJO is, at least to some extent, a coupled ocean-atmosphere mode. Several observationally based studies (e.g. Woolnough et al. 2000) have shown that the atmosphere appears to force the ocean in a systematic way during the passage of the MJO. In turn, an idealized modeling study by Woolnough et al.

(2001) has demonstrated that these intraseasonal SST anomalies can force the organisation of tropical convection in a manner that favours longer timescales (~60 days), typical of the MJO.

4.1 Vertical resolution, tri-modal convection and the Madden Julian Oscillation

Experiments using the UM with two different vertical resolutions (19 and 30 levels) have shown significant differences in the amount of variability in the tropical upper tropospheric zonal wind component associated with the MJO (Figure 6; Inness et al. 2001). Most of the extra levels were placed in the middle and upper troposphere, decreasing the layer thickness in mid-troposphere from 100hPa to 50hPa, and giving a much better representation of the temperature and humidity structure around the freezing level. The results suggested a change in the temporal organization of convection which was investigated further using an aqua-planet version of the UM. The advantages of using an aqua-planet are that the homogeneity of the set-up allows us to obtain a large sample of convective events over warm SSTs, and the removal of the land areas excludes circulations forced by land-sea contrasts. This means that convective events in different geographical locations are subject to the same large-scale forcing, giving a cleaner comparison.

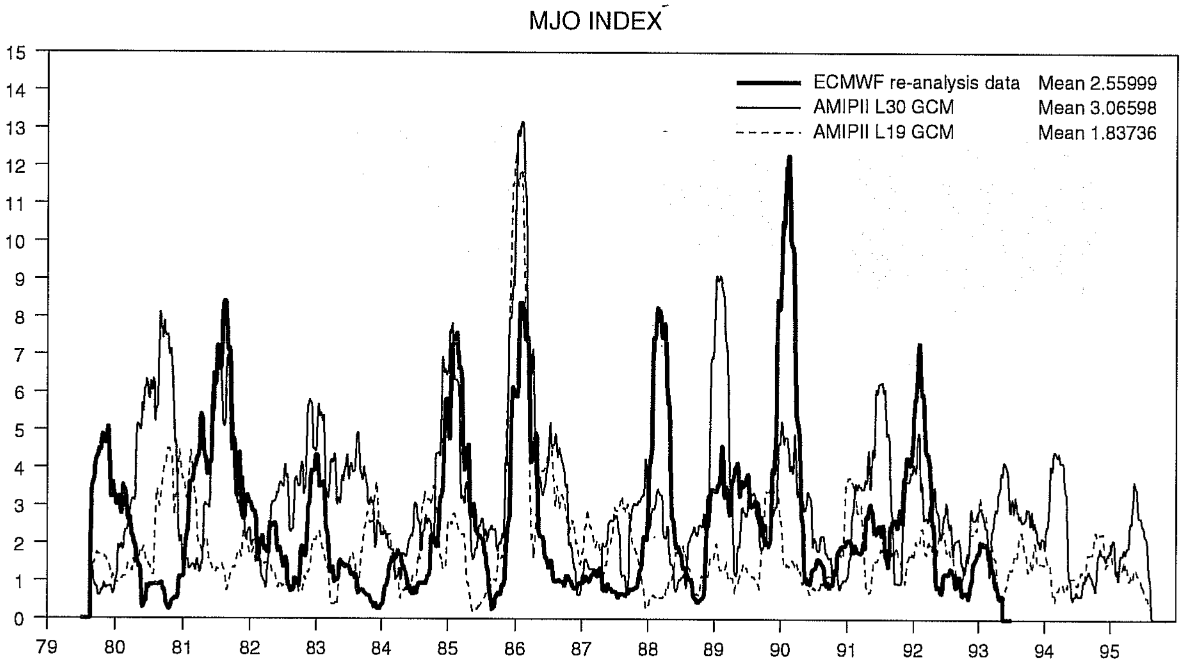
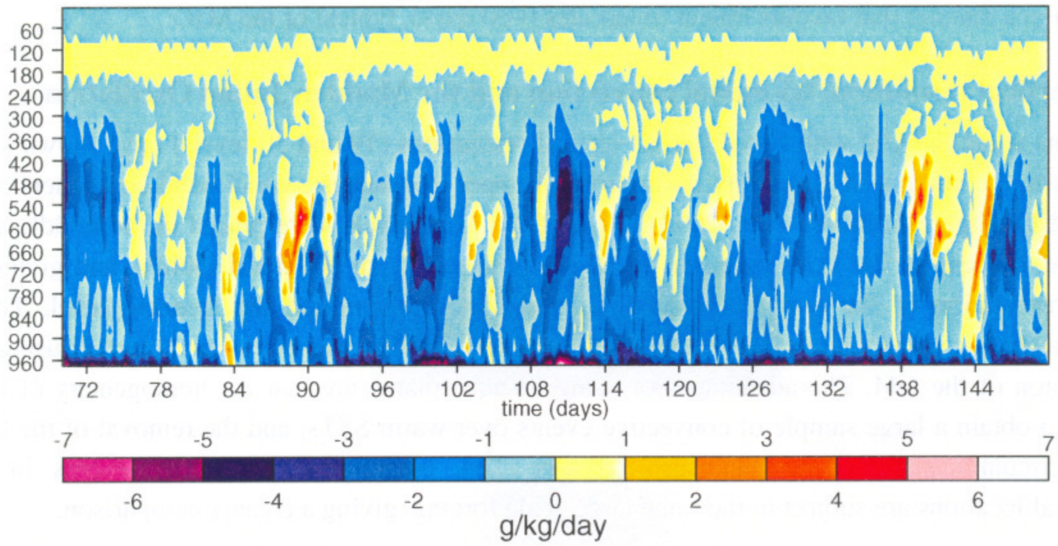


Figure 6: Time-series of an index of MJO activity based on the 20-100 day filtered variance of 200 hPa zonal wind in the Tropics. Bold line - ECMWF re-analysis data. Thin solid line - L30 GCM AMIPII integration. Dotted line - L19 GCM AMIPII integration. From Inness et al. (2001).

Many conceptual models of tropical convection are based on a bimodal cloud distribution, emphasizing shallow "trade-wind" or boundary layer cumuli and deep cumulonimbi. However, TOGA COARE results have shown the dominance of cumulus congestus clouds, and point to a tri-modal cloud distribution in which the freezing level inversion is the key (Johnson et al. 1999). The results from the aqua-planet experiments, described in detail in Inness et al. (2001), show that when the vertical resolution is increased in the UM, the spectrum of tropical cloud types changes from a bimodal distribution to a tri-modal distribution with a third peak in the mid-troposphere, near the melting level. Associated with periods when these mid-level congestus clouds are dominant, the detrainment from these clouds significantly moistens the mid-troposphere (Figure 7). In comparison, the 19-level version of the model shows no evidence of a tri-modal distribution in convection and no such moistening events.

(a) aqua-planet L30 GCM



(b) aqua-planet L19 GCM

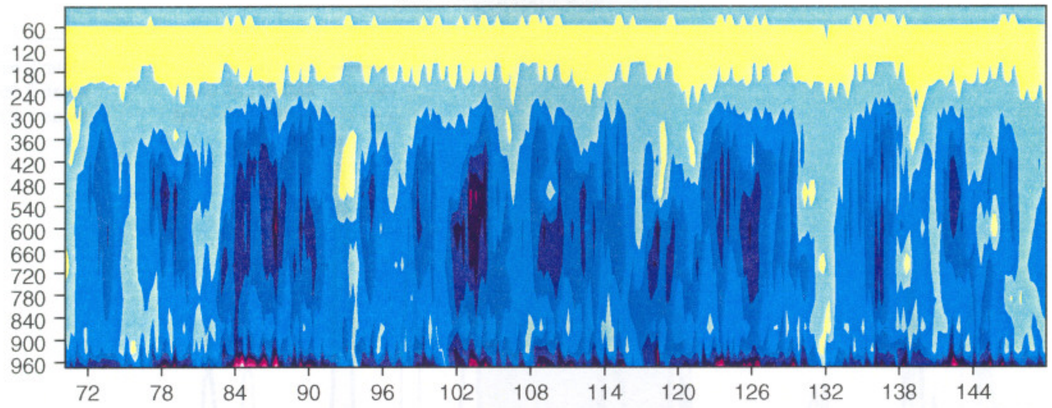


Figure 7: Time-height cross-sections of the increment to specific humidity due to the convective parametrization (g/kg/day) for a 90 day period from the aqua-planet integrations, averaged over a 3x3 grid-point box centred on the equator. (a) L30 aqua-planet. (b) L19 aqua-planet. From Inness et al. (2001).

Observational studies have shown that, during the suppressed phase of the MJO, tropical convection is dominated by clouds that terminate around the stable layer at the 0°C level (Johnson et al. 1999), and that these clouds provide a source of moisture to the mid-troposphere (Lin and Johnson 1996). Inness et al. (2001) argued that the development of a stable layer around the tropical melting level, which is frequently observed over the tropical oceans, acts to reinforce the transition from the enhanced convective phase to the suppressed phase of the MJO. Subsequently, the moistening of the mid-troposphere during the suppressed phase acts to reinforce the transition back to the active phase. This is consistent with the 'recharge-discharge' theory for the MJO proposed by Bladé and Hartmann (1993) in which the MJO timescale may be set by the time it takes for the moist static energy to build up following the decay of the previous convective event. It may be that the recharging of the moist static energy is achieved in part by the injection of moisture into the mid-troposphere by the cumulus congestus clouds that dominate during the suppressed phase of the MJO.

The appearance of these congestus clouds has been postulated as the reason for the improvement in the simulation of the MJO in the 30-level version of the UM. This is shown to be partly due to improved resolution of the freezing level and of the convective processes occurring at this level. However, the results also suggest that convection and cloud microphysics schemes must be able to represent cumulus congestus clouds which, being neither shallow nor deep cumulus as well as often weakly precipitating, tend not to be explicitly represented in current schemes.

The results of Inness et al. (2001) have emphasized the importance of vertical resolution, in line with the recent study of Tompkins and Emanuel (2000), as well as the need to properly represent the tri-modal structure of tropical convection. The importance of the cumulus congestus stage of tropical convection is being stressed here as a potentially important ingredient for the MJO. This means that vertical resolution in the free troposphere must be adequate to resolve the formation of the freezing level inversion and the cooling associated with melting precipitation.

4.2 Coupling with the upper ocean: Bringing together the diurnal cycle and the MJO

Following TOGA-COARE, it has become increasingly apparent that coupling between the ocean and atmosphere may be important for a wide range of timescales, not only those associated with seasonal to interannual variations. High frequency observations of the variations in SST taken by the WHOI surface mooring during TOGA-COARE (Weller and Anderson 1996) have shown pronounced diurnal variations in skin temperature in excess of 1K. Slower variations on intraseasonal timescales, related to the Madden-Julian Oscillation (MJO), are also evident.

A particularly noteworthy aspect of these buoy observations is the fact that the diurnal variations in SST only occur during suppressed phases of the MJO, when the winds are light and the net heat flux into the ocean is large. Furthermore, Johnson et al. (1999) showed that cumulus congestus clouds are most prevalent during light wind conditions in the presence of a strong diurnal cycle in SST. These clouds occur most frequently in the late afternoon, with a behaviour that resembles more closely the diurnal cycle in land convection, suggesting that they may be triggered by the diurnal cycle in SST. This is a strong indication that coupling with the upper ocean may be important even on diurnal timescales. Although this hypothesis has yet to be tested in fully coupled models, it is worth noting here that, although Inness et al. (2001) were able to show that increasing the vertical resolution of the model improved the subseasonal convective organisation, the observed trimodal distribution in convection was only just starting to be captured, suggesting that these diurnal variations in SST may be important.

Recent research has attempted to assess the importance of the intraseasonal SST variations seen in TOGA-COARE for determining the transient characteristics and spatial organization of tropical convection associated with the MJO. Woolnough et al. (2000) showed that, for the Indian Ocean and West Pacific, a coherent relationship exists between convection, surface fluxes and SST in which the SSTs are warmer than normal about 10 days prior to the maximum in convective activity (Figure 8). This warming is associated with increased solar radiation, reduced surface evaporation and light winds. Following the convective maximum, the SSTs cool due to reduced solar radiation and enhanced evaporation associated with stronger winds. A key requirement for the observed phase relationship between the latent heat flux, winds and convection is the presence of a westerly basic state.

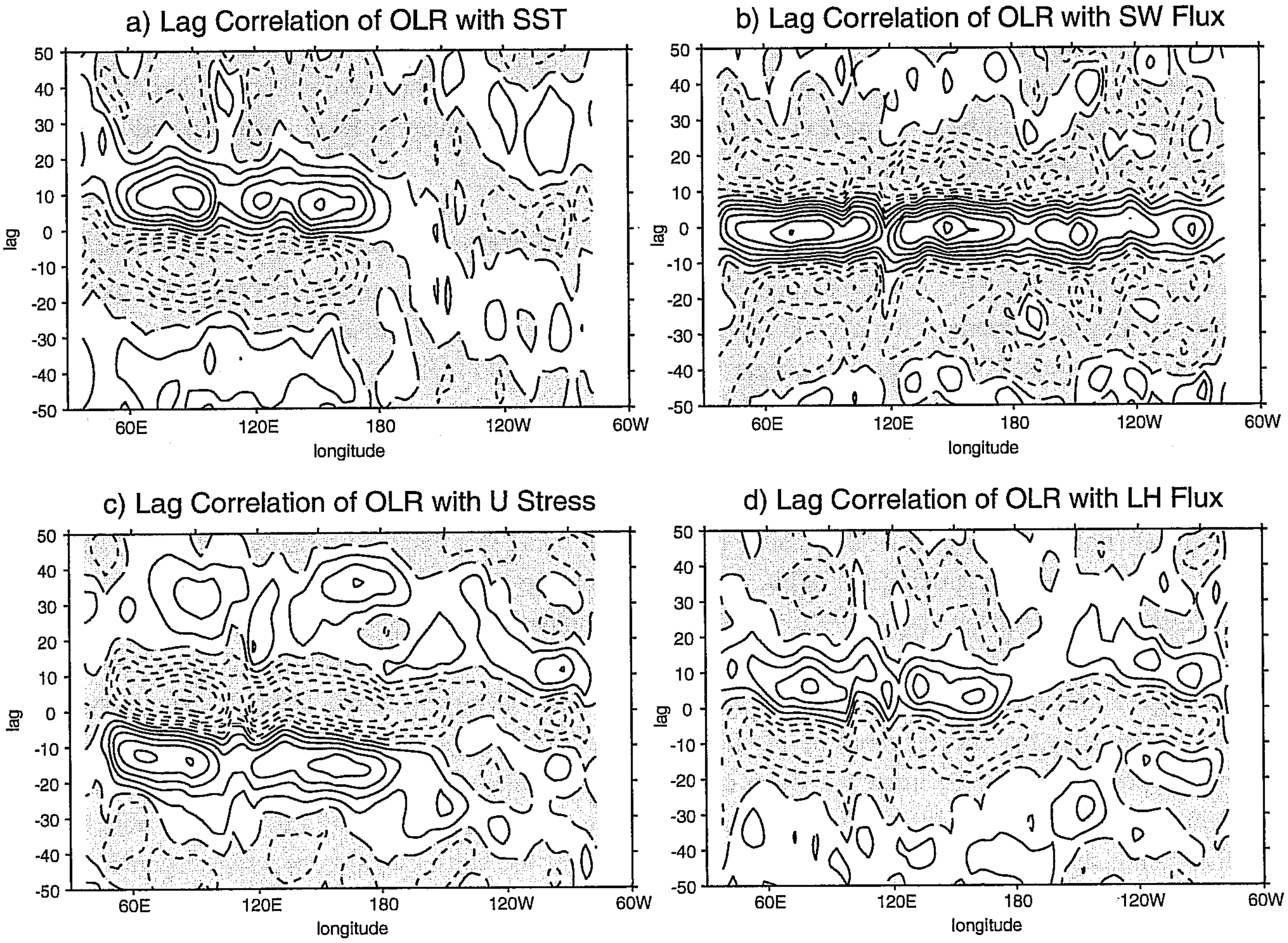


Figure 8: Lag correlations between observed OLR (convection) and surface fields: (a) sea surface temperature (SST), (b) shortwave radiation, (c) zonal wind stress and (d) latent heat flux. Negative lags indicate that the convection lags the surface field, positive lags indicates that the convection leads the surface fields. The sign convention is such that positive correlations indicate that enhanced convection (a negative OLR anomaly) is correlated with a negative SST anomaly, reduced shortwave radiation at the surface, enhanced evaporation or an easterly wind stress anomaly. From Woolnough et al. (2000).

In a related study, Woolnough et al. (2001) used the observed SST perturbations to form the basis of a series of experiments with the aquaplanet version of the UM to investigate, firstly, the organisation of tropical convection by these intraseasonal anomalies, and, secondly, how this organisation depends on the temporal behaviour of these SST anomalies. Their results showed that intraseasonal SST anomalies could potentially organise convection in a manner that favours the longer timescales (~60 days), typical of the observed MJO, and which produces a phase relationship between the convection and SST, consistent with the observed structure over the Indian and West Pacific Oceans.

There is convincing evidence, therefore, that the MJO may require coupling with the ocean in order to simulate it correctly. Preliminary studies with coupled models appear to support this conclusion (e.g. Waliser et al. 1999). Recent experiments with the coupled version of the UM (HadCM3) have shown that the organization and propagation characteristics of the MJO are improved in comparison with the results from the atmosphere-only version, HadAM3 (Figure 9; Inness et al 2002; Inness and Slingo 2002). Whereas the atmosphere-only model has a predominantly standing oscillation in the convection, the coupled model produces a more realistic eastward propagating signal. As Figure 9 shows, this is associated with coherent variations in SST; these show a similar phase relationship with convection as in observations (Figure 8), with warmer SSTs preceding the maximum in convection by between 5 and 10 days.

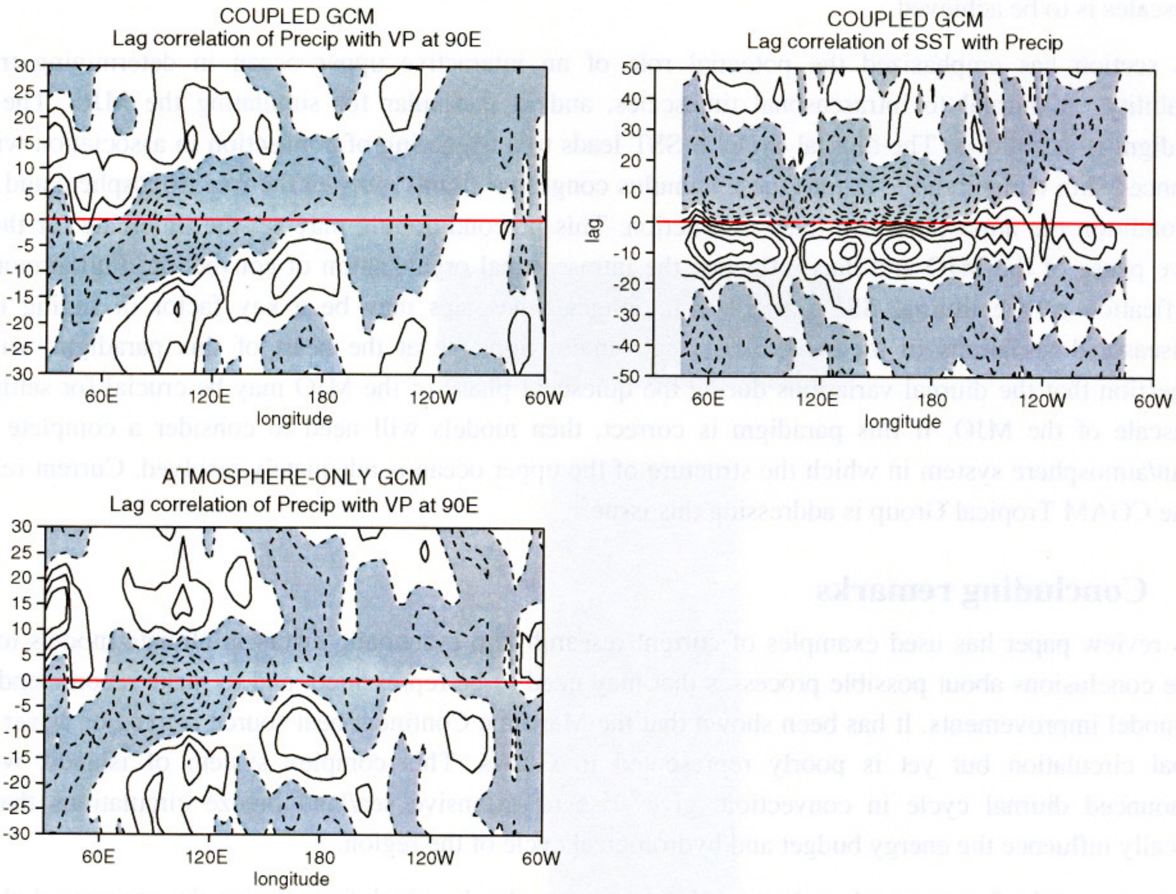


Figure 9: Lag correlations between precipitation at every longitude and an index of MJO activity at 90^{0}E, based on the 20-100day filtered 200hPa velocity potential, from (a) a version of the coupled ocean-atmosphere model, HadCM3, and (b) the equivalent atmosphere-only model, HadAM3. (c) shows the simulated lag correlations between the precipitation and SST at every longitude (as in Figure 7(a)) from HadCM3. From Inness and Slingo (2002a,b).

Whilst coupled models are capable of producing the correct relationship between convection and SST on intraseasonal timescales, supporting the notion that the MJO is at least in part a coupled phenomenon, these models still underestimate the activity of the MJO (Inness et al 2002; Inness and Slingo 2002). Although the results from HadCM3 have shown that the correct phase relationship between convection and SST can be simulated, the magnitude of the SST perturbations is smaller than observed. This is despite changes in the surface fluxes that are similar to the observed. This suggests that the representation of the upper layers of the ocean in HadCM3 may not be designed to respond realistically to subseasonal variations in winds and fluxes. Most coupled climate models have a relatively coarse vertical resolution in the upper ocean, typically of the order of 10 metres, which is therefore not sufficiently high to resolve the detailed structure of the observed mixed layer.

Lukas and Lindstrom (1991), for example, have emphasized the importance of salinity gradients within the mixed layer for modifying the coupling between the ocean and atmosphere. The large freshwater flux during the active phase of the MJO, for example, can set up a salt stratified barrier layer so that a shallow mixed layer forms which can respond rapidly to flux variations, such as the diurnal cycle in solar radiation. The TOGA COARE observations suggest that the mixed layer depth is indeed highly variable, and that the barrier layer is often as thin as a few metres during light wind conditions (e.g. Anderson et al. 1996, Inall et al. 1998, Feng et al. 2000). The presence of this barrier layer can potentially provide much stronger local coupling in the warm pool region than is currently found in coupled models which do not resolve the detailed structure of the warm pool upper ocean. This suggests that coupled models may need a more detailed representation of the mixed layer if the correct coupling between the ocean and atmosphere on sub-seasonal timescales is to be achieved.

This section has emphasized the potential role of an interactive upper ocean in determining tropical variability on diurnal to intraseasonal timescales, and in particular for simulating the MJO. The basic paradigm is as follows. The diurnal cycle in SST leads to a triggering of convection in association with the enhanced skin temperatures. In turn these cumulus congestus clouds moisten the free troposphere and hence precondition the atmosphere for deep convection. This preconditioning may set the timescale for the next active phase of the MJO and thus influence the intraseasonal organization of convection. Furthermore, the rectification of the diurnal SST variations to longer timescales may be a key factor in setting up the intraseasonal variations in the bulk SST. Scale interactions lie at the heart of this paradigm, with the suggestion that the diurnal variations during the quiescent phase of the MJO may be crucial for setting the timescale of the MJO. If this paradigm is correct, then models will need to consider a complete upper ocean/atmosphere system in which the structure of the upper ocean is adequately resolved. Current research in the CGAM Tropical Group is addressing this issue.

5. Concluding remarks

This review paper has used examples of current research into systematic errors in climate models to draw some conclusions about possible processes that may need to be represented, and to make recommendations for model improvements. It has been shown that the Maritime Continent heat source is a major driver of the global circulation but yet is poorly represented in GCMs. This complex system of islands, with its pronounced diurnal cycle in convection, gives rise to extensive sea/land breeze circulations that may critically influence the energy budget and hydrological cycle of the region.

Moistening of the free troposphere by cumulus congestus clouds, which form during the suppressed phase of the MJO, may be crucial for convective preconditioning. It has been shown that this dominant cloud type is not represented in models, which generally fail to capture the observed tri-modal distribution of convection. The importance of having adequate vertical resolution to represent the freezing level inversion has been emphasized.

Observations have shown that the diurnal cycle in SST is large during suppressed or light wind conditions in the tropics and may be a trigger for cumulus congestus clouds. SSTs also vary coherently with the MJO in such a manner as to suggest that they are an important component of the eastward propagation and timescale of the MJO. Both the diurnal and intraseasonal variations in SST involve detailed changes in the salinity and temperature structure of the mixed layer that cannot be adequately represented in current coupled models, with the suggestion that more detailed modeling of mixed layer processes in coupled models may improve the simulation of the MJO. The diurnal to sub-seasonal variations in SST and their potential importance for organized tropical convection also indicate that the use of atmosphere-only models to study atmospheric variability may be misleading. To make progress in improving atmospheric simulations and predictions, even on daily to weekly timescales, it may be desirable to develop an atmosphere/upper ocean modeling system, which would enable these potentially important couplings to operate.

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